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PRELIMINARY DATA ON THE LUNAR SOIL COLLECTED BY THE LUNA 16 AUTOMATIC PROBE

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A. P. Vinogradov

ABSTRACT. The results of preliminary studies of a sample of lunar soil taken by the automatic probe "Luna 16" are given. Information on the granulometric characteristics of the regolith, its optical properties, types of rocks, and mineral composition are described. The chemical composition of macro- and microelements for different parts of the core sample is determined for the lunar basalt. The isotopic composition of inert gases of certain elements is studied. The age was established by the Rb/Sr method as 4.85 — 4.25 billion years.

As we know, the Luna 16 automatic probe collected a sample of lunar soil taken from Mare Fecunditatis, in the northeastern part, at a point with the coordinates 0°41' S and 56°18' E, approximately 100 km west of the crater Webb (Figure 1).

Mare Fecunditatis contains traces of comparatively quiet uplifting, its borders are not marked by an annular ringwall, and its outlines are blurred. The mare is a plain with low (100 — 300 m) branching ridges traversing it. The ray systems of the large craters are not found in this area. The lunar soil from Mare Fecunditatis is characteristic of the new region of the "mare" surface of the Moon. Hence, the three large maria on the near side, arranged along the

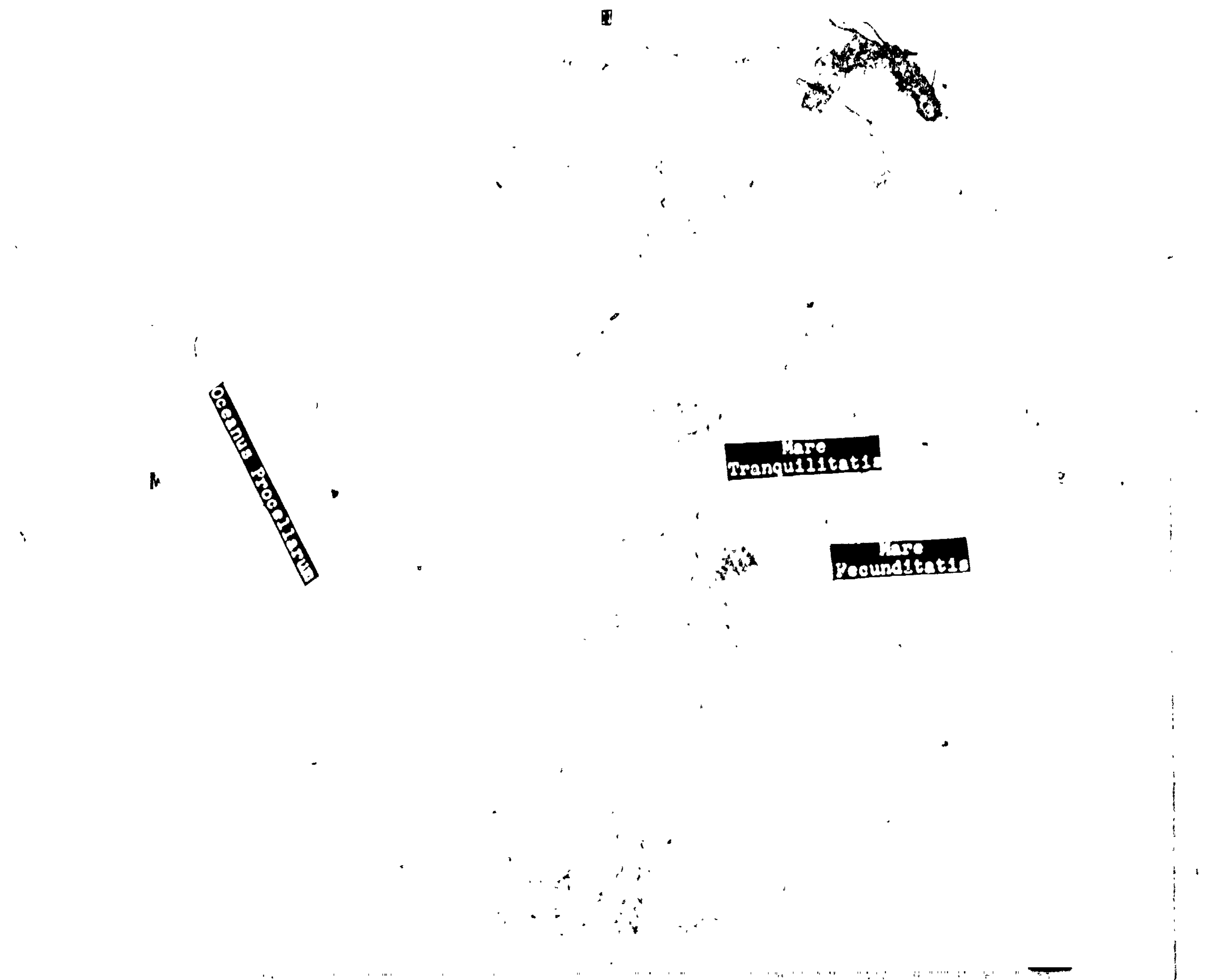

Figure 1. Map of the Moon.
• — Landing site of Luna 16; ○— Apollo 11 landing site; ● — Apollo 12 landing site.

lunar equator (Mare Tranquilitatis — Apollo 11 samples; Oceanus Procellarum — Apollo 12 samples; Mare Fecunditatis — Luna 16 samples) give a fairly complete idea of the nature of the surface rocks on the Moon.

The friable surface material of Mare Fecunditatis, the regolith, was collected by means of a drill which penetrated the rock to a depth of 35 cm. Further down, it struck hard rock or individual large fragments of rock. A column of regolith filled the core sampler. In a helium-filled chamber, the column of sandy soil — regolith -- was transferred to a collecting pan and showed no visible stratification, appearing to be uniform (Figure 2). Only a small portion of the soil in the core sample, at a depth of 35 cm, was composed of coarse-granular material. The total weight of the regolith collected by Luna 16 was 101 grams. On the whole, the regolith is a multi-granular dark-grey (blackish) powder which is easy to shape or agglutinate into individual friable lumps. The grains are either molten and rounded or angular. The granularity of the regolith increases with depth; an average grain size of 0.1 mm predominates. The numerical distribution of the grains closely follows a power law, which governs the distribution of particles in the case of repeated crushing. The median grain size in the regolith increases from the surface downward from 70 to 120 μm. On this basis,

Figure 2. Photograph of lunar soil in pan in receiving chamber. At the bottom is the deeper part of the core, where coarser material can be seen.

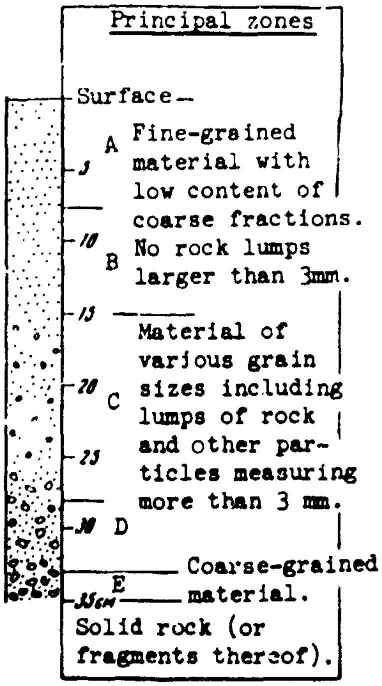

Figure 3. Schematic diagram of lunar soil core sample.

and according to the nature of the regolith core, it could be divided into several zones: A, B, C, D, and E. The regolith from each zone has been studied. Zones A and B are fine-grained material with a low content of the coarse fraction, making up 0 to 15 cm of the length of the core; C and D are composed of different grain sizes larger than 3 mm, and make up 15 to 33 cm of the core; zone E is made up of coarse-grained material and occupies 33 to 35 cm of the length (Figure 3).

Hence, the thickness of the regolith in Mare Fecunditatis at the point where the sample was collected is shallow (about 35 cm) and may possibly reach 0.5 to 1 m or slightly more when approaching the regolith in Oceanus Procellarum, where it can reach approximately 1 to 3 m, while in Mare Tranquilitatis it reaches up to 6 m. We probably still do not know the true average thickness of the regolith.

A study of the physical characteristics has indicated that the regolith has a specific gravity in natural deposits of 1 17 (1.20) g/cm^3.

Its density may be raised to 2.3 g/cm^3 by mechanical compaction. /8
The specific thermal capacity is 0.17 kcal/kg·degree, thermal conductivity is $1.9 \cdot 10^{-3}$ kcal/m·hr·degree, the specific electrical resistance is $3.42 \cdot 10^{6}$ ohms/meter, etc. This applies to the regolith, not in a natural deposit but with an environmental pressure of 10^{-6} torr and a stress of 160 kgf/m^2 on the regolith.

The optical properties were determined. In the case of Mare Fecunditatis, the average albedo was 0.069; near the landing site of the Luna 16 it was 0.105. A direct determination made on a sample of regolith yielded 0.107. .e normal albedo rises somewhat in red light: 0.086 in the ultraviolet range, 0.126 in the near infrared and 0.107 in the visible. The reflection indices clearly show the mirror component, with the angle of maximum light reflection slightly greater than the angle of incidence. This characteristic becomes more pronounced as the wavelength of the light increases and the angle of illumination decreases.

The friable soil of the lunar maria, the regolith, reveals a highly contrasty appearance under the microscope, in comparison with friable soil from Earth. The regolith also is not similar to the ash from terrestrial volcanoes. Two basic combinations of particles can be distinguished: particles of primarily magmatic surface rocks of the basalt type, as we mentioned previously in conjunction with the data from the gamma spectra of the lunar surface, obtained by the Luna 10 unmanned probe in 1966,(1) and particles which have undergone significant transformation on the surface of the Moon. The former are characterized by a remarkable bright appearance which is observed on Earth only in freshly fractured samples of unchanged rocks (they show practically no traces of rolling and are angular in shape). The latter have definite indications of melting: sintered particles of complex shape, vitrified from the surface, a significant quantity of spheric..l molten formations — like congealed droplets, with a glassy and metallic appearance, similar to the "space spherules" on Earth. These particles indicate that they were formed from liquid and hardened rapidly. The regolith particles are shown in Figure 4 as they appear under the microscope, while in Figure 5 the various particles have been collected into groups: gabbro, basalt, anorthosite, breccia, slag and cinders, glass and clinker, spherules, various particles (cf. also Figure 6). Under the scanning electron microscope, one can see (Figures 7 and 8) how the coarse silicate particles

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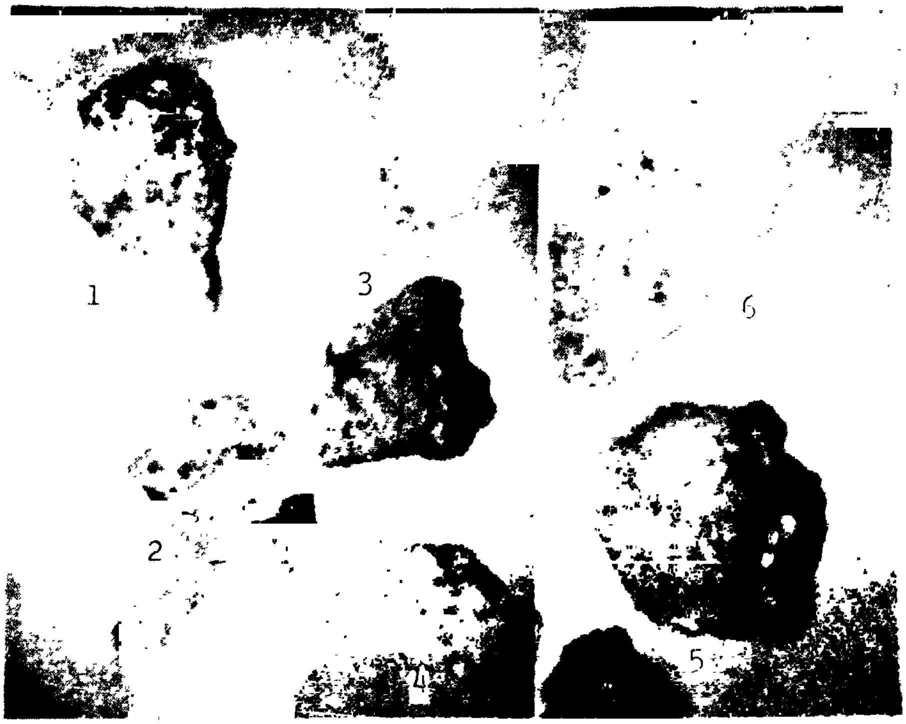

Figure 4. Large pieces of lunar rock.

1 — large-grain basalt (gabbro), leucocratic; 2 — large-grain basalt (gabbro) melanocratic; 3 — basalt, partly porous; 4 — anorthosite; 5 — breccia; 6 — molten slag particle.

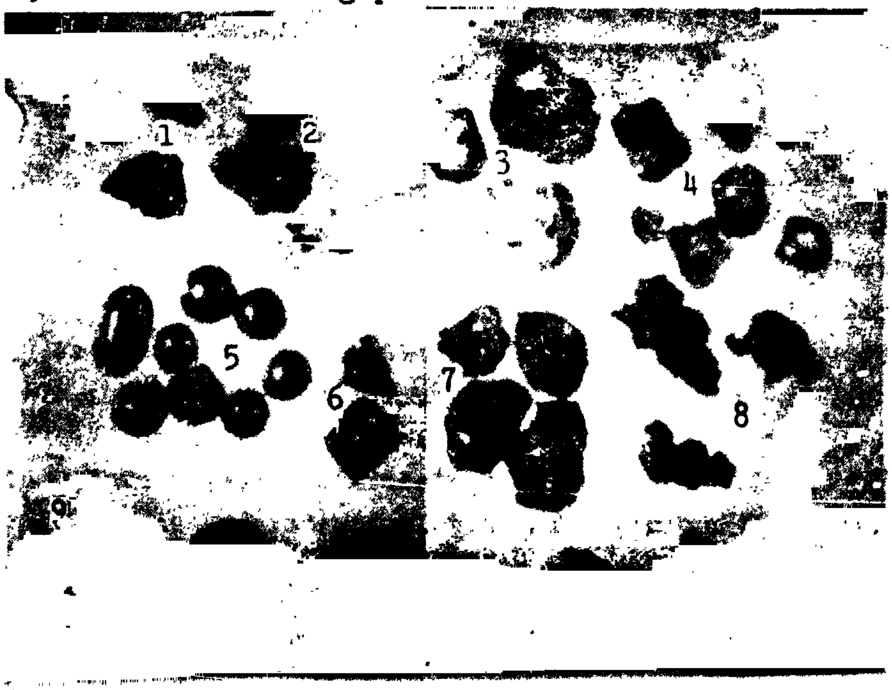

Figure 5. Groups of the most characteristic particles of lunar regolith from the +0.45 mm fraction.

1 — basalt; 2 — coarse-grained basalt (gabbro); 3 — anorthosites; 4 — uniform glasses and grains of minerals; 5 — spherules and spherical formations; 6 — turbid glass; 7 — breccia; 8 — calcined particles (clinker); 9 — slag and molten particles.

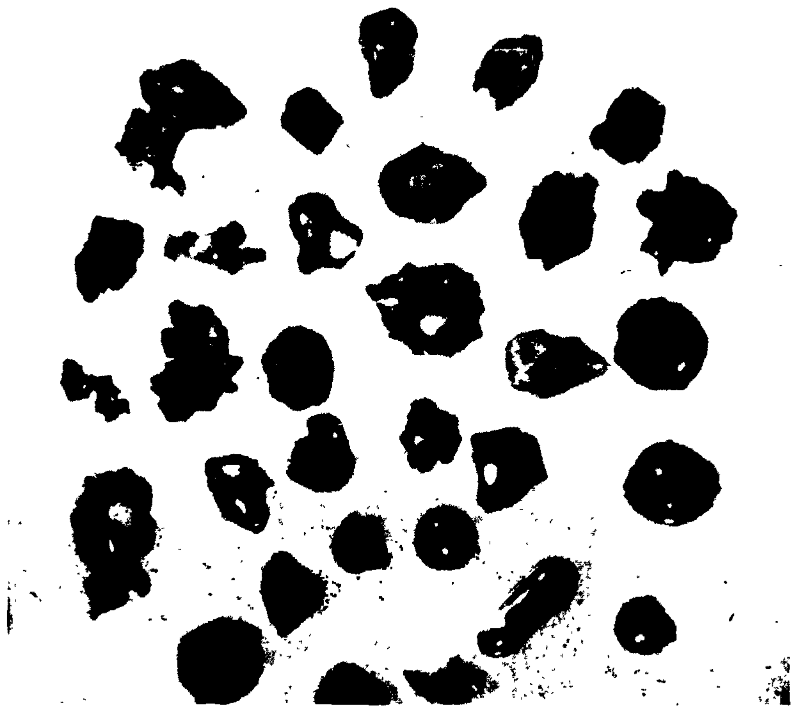

Figure 6. Various types of particles: spherules and spherical formations, glasses, clinkers.

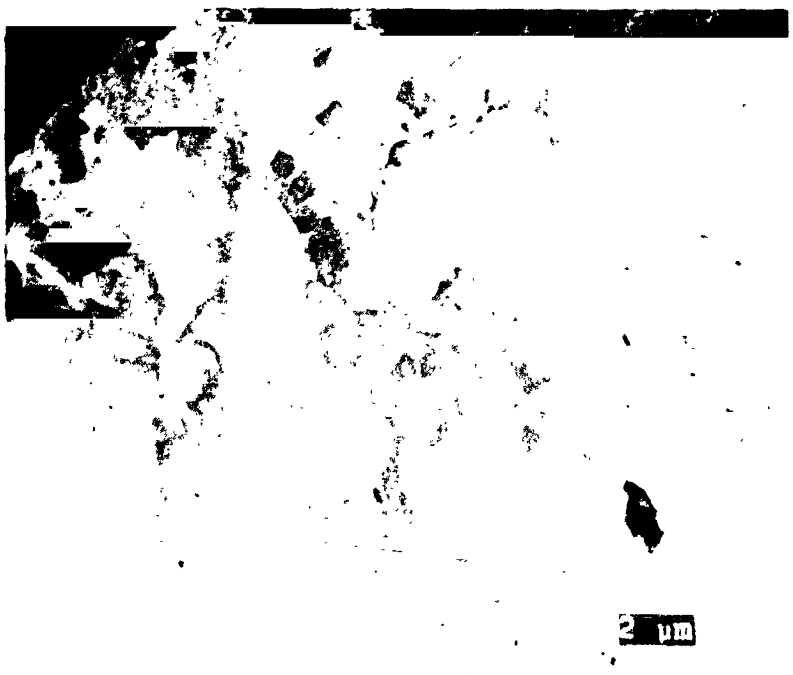

Figure 7. Scanned image of particles of the fine fraction of regolith obtained with the scanning electron microscope using secondary electrons. The large silicate particles are adhered to by the smaller ones.

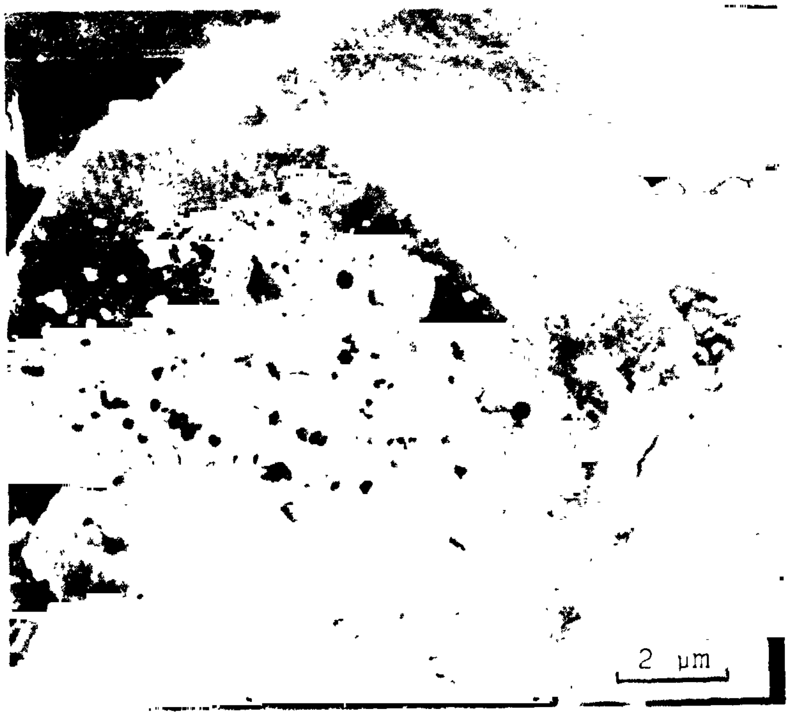

Figure 8. Scanned image of particles of the fine fraction of regolith obtained with the scanning electron microscope using secondary electrons. The large silicate particles with a cross section similar to the hexagonal and traces of protuberances on the surface are sprinkled with very fine material.

adhere to the fine fraction of other particles. The content of different particles in the regolith fraction larger than 0.45 mm is shown in Table 1.

The particles of basalt are of at least two types, characterizing the conditions of solidification of the basalt melt — fine-grained basalt (with glass) and coarse-grained basalt of the gabbroid type (Figure 9). They have an ophitic structure and make up about 1/4 of the entire coarse-grained fraction (larger than 0.45 mm). The principal materials of these rocks are plagioclase, pyroxene, ilmenite, and rarely olivine. Their relative content changes notably in various particles. Thus, we can say that a volcanic process occurred on the Moon with efflux of basalt and evidently formation of the lunar crust, whose thickness is still not known precisely.

TABLE 1

DISTRIBUTION OF PARTICLES OF DIFFERENT ROCKS BY FRACTIONS LARGER THAN 0.45 mm IN ZONES A, B, C, AND D

(PERCENT OF NUMBER OF GRAINS)

Rock	Zones			
	A	B	C	D
Gabbro	13.1	17.5	8.1	15.2
Basalt	7.3	9.0	4.9	7.9
Anorthosite	1.1	3.7	2.5	4.5
Breccia	33.9	41.4	35.5	8.3
Slags and clinkers	40.0	17.5	41.8	53.5
Glass and single grains	2.3	4.0	6.2	6.1
Spherules	1.2	1.3	1.2	1.6
Various particles	1.2	5.7	—	2.6
Total number of particles	838	297	2351	755
Weight of fraction, g	0.230	0.100	0.560	0.260

Figure 9. Section of large-grained basalt (gabbro) in polarized light using crossed nicols (enlarged). Idiomorphic grains of plagioclase and some ilmenite (black), xenomorphic pyroxene, a few extrusions of olivine.

In our opinion, this universal process of efflux of readily molten material from the Moon's core (with degassing) proceeded according to a zone melting mechanism. One finds feldspathic rocks (anorthosites), white crystalline grains. Their numbers are insignificant and their origin even on the Earth is not very clear.

Breccia — cemented, lithified rocks, formed as the result of compaction of the finely powdered material of the regolith and containing in various proportions all the components, including the particles of the primary magmatic rocks, ferronickel alloy, etc. In some breccia there has been observed a rolled form of the particles /12
and sometimes a slight compaction, which leads to their easy fracture. Breccia is magnetic; it makes up as much as 40% of the total number of particles.

Slag and cinders are fine calcined particles that form aggregates of very complex irregular branching shape. All of the components of the regolith are included in their composition.

Glass, vitrified and calcined particles make up at least half of all the particles of regolith. Depending on the composition (content of Fe, Ti, etc.), they have colors that range from dark brown to black. One sees both bubble-like slag-type melting and smooth glaze-like vitrification. This is typical lunar melting, which takes place during the instantaneous heating of a completely cold particle.

Solidified drops — spherules and similar formations are found in different shapes — pear-shaped, dumbbell-shaped, etc., and transparent, cloudy-white, greenish, yellowish-turbid and opaque. Some are hollow. Their sheen ranges from glassy to metallic; their numbers increase among the fine fractions. They are formed at temperatures far in excess of the temperature of molten rock, when they spray out in the molten state.

Finally, there are the grains of individual minerals: plagioclase, olivine, anorthite, pyroxene, spinel, ilmenite, iron particles, etc. Table 2 gives some idea of the nature of the content of various minerals in the regolith. It follows from the data in the table that the content of olivine, for example, on the whole is quite significant and approaches its content in the regolith in the Apollo 12 samples, while the olivine content in the Apollo 11 samples is much less. However, the content of ilmenite, for example, is similar to the content in the Apollo 12 samples, while there is much more of it in the Apollo 11 samples than in those from Luna 16 and Apollo 12. Olivine occurs in the regolith only in the form of individual monocrystalline fragments of irregular shape (acute-angled pieces) of different colors, as well as in the composition of gabbro particles. X-rays reveal the lack of lattice deformation and the effects of twinning, i.e., the absence of lattice stress. This is the ordinary alpha modification of olivine; it is characterized by a non-ordered distribution of magnesium and iron atoms in the structure. From the data of micro-X-ray spectral analysis of a section of a silicate particle of this /13
type, it is evident that it has the following composition (wt. %): SiO_2 — 36.0, MgO — 27.5, FeO — 33.8, CaO — 0.38, MnO — 0.29, Cr_2O_3 — 0.15, Al_2O_3 — 0.05, TiO_2 — 0.01, CoO — 0.03, NiO < 0.01, Σ — 98.2. This is a homogeneous crystal of olivine whose iron content is 40 mol. % Fe_2SiO_4 and corresponds to the molecular formula

$$[Mg_{1.14}Fe_{0.78}(Ca, Mn, Cr)_{0.08}]SiO_4.$$

The most widespread mineral in the regolith is anorthite, followed by augite and ilmenite. Anorthite is found in the form of fine-crystalline aggregates in samples of basalt, gabbro, spherules and in fine fractions of regolith. No individual single crystals were found.

Plagioclase is found also in the form of single crystals with triclinic symmetry. The pyroxenes of the augite-pigeonite type are found in pieces of rock where in many cases they play the primary role in basalt and gabbro. X-ray spectral analysis has been used to

TABLE 2

RESULTS OF MEASUREMENTS OF MOSSBAUER SPECTRA OF LUNAR MATERIAL

Material	Fraction of total area of Mossbauer spectrum of iron-containing mineral, %				
	USSR (Luna 16)			USA (Apollo 11)	
	Sample				
	A3-1	A3-3	D8-2	84-14	45-24
Ilmenite	7.7	6.7	9.2	19.7	26.9
Pyroxene	69.0	71.5	65.1	67.6	60.8
Olivine	18.8	16.7	25.5	4.4	6.1
Iron	4.5	5.1	not determined	5.8	2.1
Troilite	≤1	≤1	≤1	≤1	≤2
Magnetite	≤2	≤2	≤2	1.4	2.1

study the distribution of elements in sections of basalt, which has made it possible to identify the minerals (Figure 10).

Ilmenite is found in the bulk sample of regolith, sometimes in combination with augite. Chromium spinel has been seen in the form of single dark crystals. As far as magnetic material is concerned, micro X-ray spectral analysis can be done on Sample 3-4b. Analysis with the surface intact (without preparing a section) reveals the irregular distribution of Fe, Ni, Cr, Ti, Si, Al, Mg, and Ca. Zones can be distinguished with lithogenic elements and zones with increased concentrations of Fe (6%) and Ni (1%) (Figure 11). At some points, an iron content of up to 66% is seen, while the amount of nickel may reach 6%. However, it has not been possible to use the Mossbauer spectroscopic method to detect nickel in magnetic particles. X-ray analysis of iron particles reveals alpha-iron, i.e., kamacite. Tenite could not be found. The volume of iron particles does not reach 1% in the regolith. It is difficult to say anything definite at the present time concerning the origin of these particles. As we shall see later on, the quantity of nickel in the regolith in comparison with its content in monolithic rock (basalt) is higher in the case of the Luna 16 material and also in that from Apollo 11 and 12 by a factor of 5 on the average, while the amount of cobalt increases by a factor of 1.5 at the most. In addition, we see a very low content

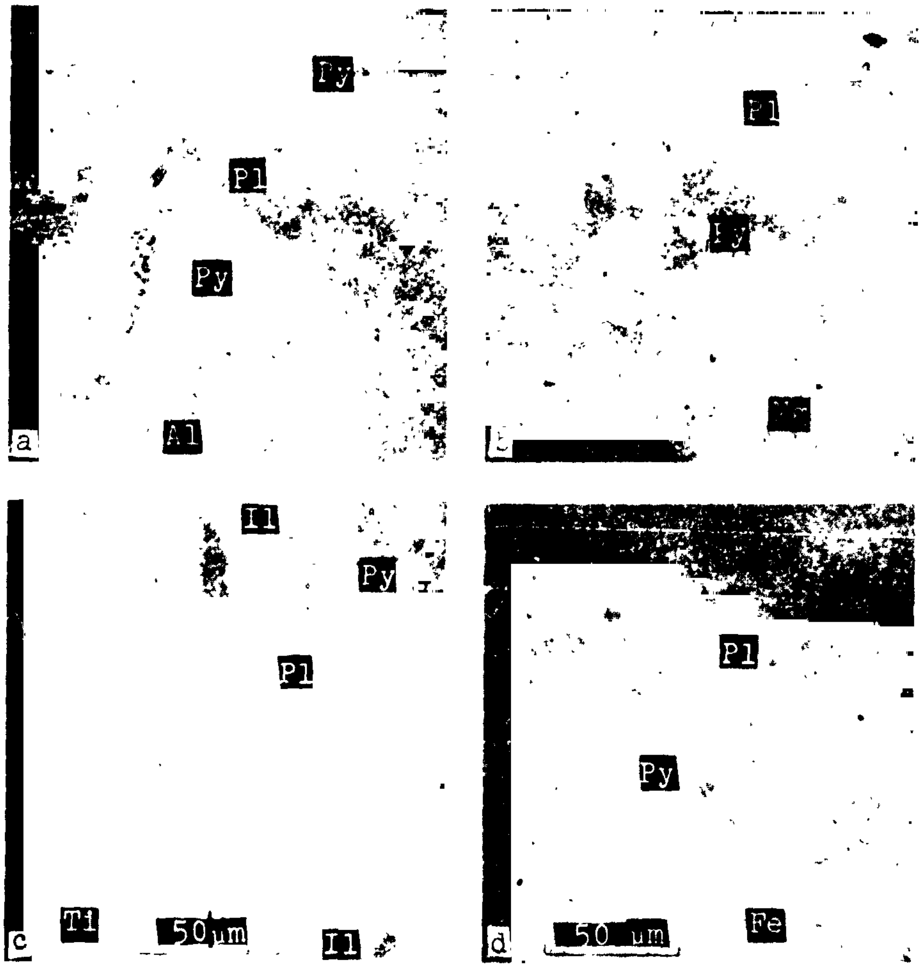

Figure 10. Photograph of portion of section of coarse-grained basalt (gabbro) obtained on X-ray microanalyzer.

a — aluminum distribution pattern; b — magnesium distribution pattern; c — titanium distribution pattern; d — iron distribution pattern. Minerals: Py — pyroxene; Pl — plagioclase; Il — ilmenite.

of platinoids in the regolith, while in the iron meteorites there are hundreds of times more of them than in the rocks. A chemical analysis was performed in parallel with the X-ray spectral analysis (mainly for the basic elements) and the mass-spectral (all elements) and spec- /14
tral as well as activation methods — selectively, for individual elements (Table 3).

Figure 11. Scanned pictures of magnetic particle recorded on X-ray microanalyzer.

a — image with absorbed electrons; b — iron distribution pattern; c — silicon distribution pattern; d — nickel distribution pattern.

TABLE 3

CONTENT OF MACROELEMENTS IN REGOLITH FRACTION FROM ZONES A, B, C, AND D (X-RAY METHOD), wt., %

Component	Regolith				Basalt	Component	Regolith				Basalt
	A	B	C	D			A	B	C	D	
SiO_2	41.7	41.2	42.5	41.3	43.8	ZrO_2	0.015	—	0.013	—	0.04
Al_2O_3	15.32	15.40	15.45	15.15	13.65	Cr_2O_3	0.31	0.25	0.30	0.26	0.28
FeO	16.80	16.55	16.30	16.90	19.35	MnO	0.21	0.20	0.20	0.22	0.20
CaO	12.20	12.80	12.42	12.55	10.40	Na_2O	0.37	0.36	0.36	0.28	0.33
MgO	8.73	8.82	8.96	8.60	7.05	K_2O	0.10	0.12	0.10	0.10	0.15
TiO_2	3.39	3.46	3.30	3.42	4.90	S	0.19	0.20	0.18	0.25	0.17

As we can see, the variations in the principal composition of /15
the regolith on four levels were insignificant. The differences in content between the regolith and the basalt were much more striking. If we compare the composition of the Luna 16 rocks with the rock samples collected by Apollo 11 and 12, the differences are not so great on the whole, with the exception of the content of Ti, Zr and several other chemical elements that are found in the lunar rocks in small amounts (trace elements) (Table 4). Mention should be made of the high contents of F, S and Cl and other volatile elements which have dissipated away from the Moon. However, vacuoles are found in particles of regolith that may possibly contain common gases; they are being studied.

A comparison of the chemical composition of the regolith and the monolithic rocks of the three maria indicates that the material has the exact same nature everywhere, with variations in the composition of both the regolith and the monolithic rocks. The most marked difference in the composition of the Luna 16 rocks consists in the low Ti content. It is practically the same as in the rocks from Oceanus Procellarum (Apollo 12) but nearly half that in Mare Tranquilitatis. The variations in the content of Mg and Fe are small (Table 5).

The highest Zr content is found in the crystalline rocks from Mare Tranquilitatis, where there is a great deal of Ti, Y and Sc. The content of the majority of macroelements as well as Ni and many microelements in the three maria is practically the same. The Ni
content in the regolith from the three maria is strikingly similar. /16
The variations in the composition of the regolith and continental rock of a given mare is of the greatest interest. These variations are repeated in the three maria. For example, the content of Fe, Ti and Zr is always higher in the continental rock than in the regolith. However, the Ni content is always higher in the regolith than in the crystalline rock. Similarities in the Ti content in the crystalline rocks and in the regolith indicate that the regolith was formed on the spot and was not conveyed from a distance (like volcanic ash). The amount of Ca increases in the regolith as does the amount of Al_2O_3.

TABLE 4

CONTENT OF TRACE ELEMENTS IN ROCKS COLLECTED BY LUNA 16 (MASS SPECTRAL DETERMINATIONS), ppm

Element	Regolith A	Regolith B	Regolith C	Regolith D	Basalt
Li*	—	10	—	10	—
Be*	—	2.8	2	2.7	—
F	265	292	246	277	181
B	4.5	3.9	6	4.6	5
P	—	254	—	200	511
Sc	27	33	23.3	25	20
CL	66	74	36	72	—
V	64	73.5	55.3	55	42.5
Co	68	56	44	61	29
Ni	190	137	250	178	147
Cu	36	39.8	35	36	13
Zn	10	20	33	21.5	26
Rb	3	6.3	5.5	—	—
Sr	90	156	—	182	445
Cs	0.06	0.26	—	0.08	0.75
Zr	350	334	354	346	—
Hf	1.1	3.6	1.2	1	0.3
Mo	7	12	3.6	5	1.2
Ga	11	—	4.9	—	1.2
Ge	1.3	1.2	1.2	1.5	2.5
As	0.4	0.36	0.6	0.3	2.9
Se	0.45	0.5	—	0.4	0.7
Br	0.26	0.27	0.24	0.33	1.3
Ru	0.03	0.044	0.01	—	6
Rh	—	0.0037	—	—	—
Pd	0.0086	0.012	—	0.01	0.027

Element	Regolith A	Regolith B	Regolith C	Regolith D	Basalt
Ag*	0.05	0.059	0.02	0.07	0.2
Cd	1	0.75	1	1.3	—
In	0.06	0.025	0.086	0.08	—
Ba	42	259	37	48	206
Sn	1.6	1.4	—	2	4
Sb	0.4	0.3	0.7	0.35	0.5
Te	0.2	—	0.15	0.2	—
W	—	4.7	5.3	5.7	9
Au	—	0.0013	0.003	—	—
Tl	—	0.2	—	0.5	—
Pb	—	6.6	7	6	7.7
I	—	—	0.26	0.14	—
Y	45	49	50	56	58
La	7.3	8	7.4	7.2	7.7
Ce	21	26	24	23	24.6
Pr	4.5	4.7	4.6	4.5	4.8
Nd	20	28	21	23	25
Sm	5.6	6.8	2.6	6.8	7.1
Er	1.6	1.2	1.3	1.4	1.2
Gd	6.0	4.7	4.6	5.8	4.8
Tb	0.75	1.0	0.9	0.9	0.9
Dy	5.0	5.3	5.0	5.0	5.2
Ho	2.0	2.2	1.9	1.8	2.0
Er	5.0	5.0	5.0	4.7	5.0
Tm	0.4	0.4	0.4	0.4	0.4
Yb	3.4	3.6	3.5	3.5	3.5
Lu	0.28	0.3	0.3	0.3	0.3

*Spectral determination.

TABLE 5

COMPARISON OF COMPOSITION OF REGOLITH AND CRYSTALLINE ROCKS FROM THREE MARIA

Component	Crystalline rocks			Regolith		
	Area where collected					
	Mare Tranquilitatis, Apollo 11	Oceanus Procellarum, Apollo 12	Mare Fecunditatis, Luna 16	Mare Tranquilitatis, Apollo 11 (average)	Oceanus Procellarum, Apollo 12	Mare Fecunditatis, Luna 16 (average)
	Weight percentages					
SiO_2	41	40	43.8	43	42	41.7
Al_2O_3	12	11.2	13.65	13	14	15.33
TiO_2	10	3.7	4.9	7	3.1	3.39
FeO	19	21.3	19.35	16	17	16.64
MgO	8	11.7	7.05	8	12	8.78
CaO	10	10.7	10.4	12	10	12.49
Na_2O	0.5	0.95	0.38	0.54	0.4	0.34
K_2O	0.12	0.065	0.15	0.12	0.16	0.10
MnO	0.4	0.26	0.20	0.23	0.25	0.21
Cr_2O_3	0.6	0.55	0.28	0.37	0.41	0.28
ZrO_2	0.1	0.023	0.04	0.05	0.09	0.013
NiO	(0.007)	—	0.04	0.03	0.025	—
	ppm					
Rb	2.5	0.64	—	2.2	3.2	5.9
Ba	90	72	206	68	420	114
Sr	110	145	445	90	170	169
Yb	2.5	—	3.5	2.5	—	3.5
Y	250	51	54.0	130	130	58.0
Zr	700	170	300	400	670	347
V	45	88	42.5	42	64	61
Sc	110	50	20	55	47	27
Ni	55	54	147	250	200	190
Co	9	40	29	18	42	53
Cu	5	—	13	—	—	37
Li	15	5.5	—	15	11	10*
Ga	6	—	11	—	—	4.9

*Spectrally, all others mass-spectrally.

Hence, the regolith is enriched with plagioclase and impoverished with respect to pyroxene, olivine, ilmenite (and spinel), i e., the crystalline rocks are more maphic than the regolith. The rare lithophilic elements are usually found in the crystalline rocks of Mare Tranquilitatis: Y, TR, Zr, Cr, and Th and U as well (Table 6).

TABLE 6

CONTENT OF Th AND U, ppm

Element	Regolith			Crystal rocks		
	Apollo 11	Apollo 12	Luna 16	Apollo 11	Apollo 12	Luna 16
Th	2.24±0.06	6.0±0.6	0.474±0.05*	2.9±0.4	0.88±0.09	1.4±0.1*
U	0.59±0.02	1.5±0.2	0.1±0.01*	0.7±0.1	0.24±0.0035	0.2±0.02*
Th/U	3.8	4.0	4.7	4.0	3.7	5.7

*Determined mass-spectrally

We have already called attention to the low content of platinoids and gold in the regolith. We still do not have a great deal of data in this regard, but the following distribution of platinoids and gold can be seen in the lunar rocks (Table 7).

TABLE 7

DISTRUBUTION OF PLATINOIDS AND GOLD IN LUNAR ROCKS, ppm

Rock	Pt	Pd	Ir	Ru	Rh	Au
Terrestrial basalt	0.02	0.02	—	—	—	0.004
Lunar crystalline rocks collected by Apollo 11	—	0.006*	0.01	—	—	—
Apollo 11	—	0.1**	0.0001	—	—	0.0016**
Apollo 12	—	—	0.0013***	—	—	0.0011***
Luna 16	—	0.027	—	6.3	—	—
Regolith collected by Apollo 11	—	0.04**	—	—	—	0.0021****
Luna 16	—	0.01	—	0.027	0.0037	0.002
Iron meteorites	12.0	3.7	2.8	—	—	1.0

*Baedecker, Wasson — Science, 1970, 167, N 3918.
**Morrison, et al. — Science, 1970, 167, N 3918.
***Laul, et al. — Earth and Planet. Sci. Lett., 1970, 9, N 2.
****Wanke, et al. — Science, 1970, 167, N 3918.

The determination of all the rare earths is not yet complete. The isotopic analysis of Li^7/Li^6 for the regolith is 12.28; K^{39}/K^{41} — 14.00 ± 0.18; Rb^{85}/Rb^{87} for an average sample is 2.57 ± 0.04, i.e., the isotopic composition corresponds to that of these elements on Earth. On the other hand, for example, a disruption of the isotopic composition has been observed for lithium in meteorites.

As we know, shearing products are produced in rocks under the influence of the "solar wind." They have been observed in the regolith — Na^{22}, Al^{26}, etc. For example, Al^{26} yields 173 ± 113 disintegrations/minute/kilogram. This work is continuing and we hope to have data on both the zone A fraction and the zone D fraction from the deeper part of the regolith core. This would make it possible to explain more. /17

It is interesting to mention in this connection that the infrared spectrum of the regolith has revealed the presence of a broad unstructured absorption band in the region of the oscillations of the silicate bonds. Calcination of the regolith sample in an argon atmosphere up to 1000° C leads to the appearance in the IR spectrum of a distinctive structure — individual bands associated with the absorption of isolated and combined SiO_4 groups, framework silicates, etc. Consequently, we can assume that there has been an irradiation of the regolith material and the possible changes that occurred as a result of this are removed by calcination.

The "solar wind" acts on the rock, causing its metamictization and the formation of shearing products to a shallow depth, about 3 — 5 cm. Hence, we decided to measure the activity both in the upper layers of the regolith and in its base. The results may explain the history of the accumulation of the regolith.

The regolith contains inert gases of unusual composition; the latter is independent of the depth of the regolith (the regolith sample is from zone D) (Table 8). /18

TABLE 8*

CONTENT AND ISOTOPIC COMPOSITION OF INERT GASES IN DUST SAMPLES (IN 10^{-8} cm^3)

Isotopes	Mare Fecunditatis sample D-7	Apollo 11		
		Schaffer, Zahringer	Reynolds	Hindenberger
He^4	18000000	11000000– 19000000	29000000	9000000
He^4/He^3	2670	2540	2130	2770
Ne^{20}	340000	313000	530000	125000
Ne^{20}/Ne^{22}	12.80	12,4	12,85	12,6
Ne^{21}/Ne^{22}	0.0352	0,0340	0,0332	0,0332
Ar^{40}	53000	38500	57000	56000
Ar^{40}/Ar^{36}	0.98	1,1	1,126	3,04
Ar^{36}/Ar^{38}	5.26	5,20	5,19	5,08
Kr^{84}	22	21	37	8,5
Xe^{132}	8.5	10	4,6	2,2

*[Translator's Note: Commas represent decimal points.]

The predominant component of the gases is the gases of the "solar wind." Their composition differs sharply from that of terrestrial gases and gases from meteorites. The concentration of the gases is very high, several orders higher than in terrestrial objects and in meteorites. The He and Ne contents are about the same as in several meteorites that are rich in neutral gases. They are usually distinguished by an isotopic composition with Ar — for example, $Ar^{40}/Ar^{36} \sim 1$, and $Ar^{36}/Ar^{38} \sim 5.25$ corresponds to that on Earth. The amount of Ar^{40} is 4 to 5 times greater than the amount which could be formed in the rocks as a result of the decay of K^{40}. The isotopic composition of Xe also differs from that on Earth and is being investigated further. On the basis of the content of inert gases, the substance of Mare Fecunditatis is closer to the regolith of Mare Tranquilitatis. The first determinations of the age of the Moon have been made using the Rb/Sr method and the fine fraction of the regolith, which gave a figure of ($4.85 \cdot 10^9$ to $4.25 \cdot 10^9$) $\pm$ $0.75 \cdot 10^9$ years. The average along the isochron is 4.45 and $4.65 \cdot 10^9 \pm 0.5 \cdot 10^9$ years. Hence, the samples from the three maria are very similar in absolute age, i.e., the age of the Moon corresponds to the age of the Earth. The same values are obtained according to Pb^{206}/Pb^{207}. The age according to the K/Ar method is difficult to calculate. The exposure time of the regolith is of particular interest.

Hence, the lunar rocks from the three maria are of a single common type (basalt), and the variations in their composition are a function of the conditions of their melting, while those of the regolith are due to its somewhat different history.

The rocks from Mare Fecunditatis, as we have seen, resemble those /19 from Oceanus Procellarum. However, they resemble the regolith of Mare Tranquilitatis, for example, in their content of neutral gases in the regolith.

Let us formulate some preliminary concepts. It is still premature to make a conclusive statement regarding the nature of the processes on the lunar surface. We shall limit ourselves to the data obtained from the study of the rock samples brought by Luna 16 from Mare Fecunditatis and naturally compare them with the data collected on the flights of the Apollo 11 and 12. The material from all three maria — Mare Tranquilitatis, Oceanus Procellarum and Mare Fecunditatis — is surprisingly similar in its petrological, mineralogical and chemical composition. The vast lunar maria, located along the Moon's equator, are depressions that were flooded with basic lava at some time in the past. Long ago, during the era of intensive volcanic activity, an enormous mass of basalt flowed out onto the lunar surface, accompanied by the dissipation of gases. Depending on the conditions of the eruption, the depth, temperature, etc., the basalt surface rock on the Moon differs in terms of the content of Fe, Ti, Zr, Ba and other elements. The iron content of the magma was not the deciding factor in this endogenic process. It is possible that rocks will be found on the Moon which are derivatives of basalt (anorthosites, rhyolites). We do not know exactly the depth of the basalt crust of the Moon. The absolute age of the surface rocks of the Moon (rather, the age of the Moon) is practically the same as that of the Earth. The lunar maria are covered by a layer of regolith. Its thickness is evidently quite variable, and in Mare Fecunditatis, at the site where the Luna 16 sample was collected, it was a maximum of 0.5 meter. The limits of variation probably amount to several meters. As we have already seen, the regolith is an inhomogeneous mixture of grains of rock, minerals of various sizes, shapes and colors — both molten and particulate. With depth, the ratios between the various grains change, although no stratification of the material can be seen. This material is the result of powdering of rock under the influence of high temperature, causing the formation not only of molten particles of regolith but of spherules as well. The regolith does not resemble the volcanic ash from terrestrial volcanoes. As we have seen, the composition of the regolith differs slightly from the composition of the lunar crystalline rocks. It contains a reduce amount of maphic elements, and consequently must be more molten than the primary basalt. Before touching on the problems of the formation of the regolith, let us recall the main factors of lunar "erosion." First of all, there is the temperature variation of the lunar surface rocks in the course of billions of years, from lunar day to lunar /20 night — over a temperature range of ± 100° C. Then there is the irradiation of the surface rocks of the Moon by the "solar wind" and the galactic cosmic radiation. Furthermore, there is the vacuum in which the lunar rocks are located; finally, the possible impacts of meteorites are involved as well. Probably the temperature drop of the surface rocks on the Moon has some effect on their hardness, but we are not in any position to measure this at the present time.

The "solar wind" and galactic radiation have a much more significant effect. First of all, it would seem from our observations that the entire regolith shows signs of the influence of the "solar wind" to a depth of 35 cm. In a sample from zone D, the regolith contained an enormous amount of solar neutral gases.

Then the infrared spectrum of the regolith indicates that it has been irradiated. We must await the determination of the radioactive products of splitting from the deep layers of the regolith. All of this is a preliminary indication either of the displacement of the regolith at the site, or the fact that the history of its formation is written in its strata. Radiation does not penetrate deeply; it only passes through the first few centimeters of soil. On the basis of the observations and study of the so-called metamiction in minerals containing radioactive elements, we can conclude that they lose hardness and undergo deformation of their crystal lattices. However, this usually does not lead to a complete disruption of the minerals. We are attempting to detect metamiction in particles of regolith. In addition, radiation begins to have an effect, especially when the mineral is already fractured. Hence, during the crumbling of the material, the "solar wind" does not participate directly in the formation of the regolith (melting) and does not affect the strength of the material. Usually the formation of the lunar maria and consequently the regolith in particular, which fills them, is linked to the action of falling meteorites and their impacts. It is interesting to think of the fall of a swarm of meteorites on the side of the Moon that faces the Earth in the region of the present lunar maria, which are located along the equator. Why did they fall in swarms only on the visible side of the Moon, the most convex part that faces the Earth? This is difficult to explain. The most reliable proof of the "work" of meteorites would be their observation on the lunar surface. However, meteorites and micrometeorites strike the Moon at cosmic velocities. Experiments and calculations show that 1 gram of meteorite substance under these conditions would be capable of excavating an amount of lunar rock that is 2 — 3 orders larger, pulverizing it, etc. The rock particles would strike with enormous velocities (over a broad spectrum). Some could escape from the Moon, breaking free of its gravity, and reach the Earth (for example, eucrites). We must always keep in mind this situation with the balance of matter on the Moon, when trying to find an explanation for the formation of the regolith. However, some portion, admittedly very small, of the meteorite substance will remain on the lunar surface. Earlier, we presented preliminary data on finding meteoritic material in the regolith. It will undoubtedly be found. But this is far from being a sufficient explanation of the formation of all the regolith on the Moon.

The most striking fact about the endogenic process of the eruption of basalt on the Moon is the instantaneous contact with the vacuum of space. The lunar magma reaches the crust and breaks through. The liquid magma and its gases burst out into a vacuum. There must be a spraying of the liquid magma and a simultaneous loss of its gas and other volatile components. It would be desirable to find on this "endogenic track" the explanation for the origin of the regolith by conducting appropriate experiments. This is especially true, because the main question regarding the nature of the balance of the lunar material is critical to an understanding of geochemical processes on Earth, especially during the first billion years of its evolution.